Abstract. We have estimated monthly values of the $J_2$ and $J_3$ Earth gravitational coefficients using LAGEOS satellite laser ranging (SLR) data collected between 1980 and 1989. For the same time period, we have also computed corresponding estimates of the variations in these coefficients caused by atmospheric mass redistribution using surface atmospheric pressure estimates from the European Center for Medium Range Weather Forecasts (ECMWF). These data were processed both with and without a correction for the "inverted barometer effect," the ocean's isostatic response to atmospheric loading. While the estimated zonal harmonics in the orbit analysis accommodate gravitational changes at a reduced level arising from all other higher degree zonal effects, the LAGEOS and atmospheric time series for $J_2$ compare quite well and it appears that the non-secular variation in $J_2$ can be largely attributed to the redistribution of the atmospheric mass. While the observed changes in the "effective" $J_3$ parameters are not well predicted by the third degree zonal harmonic changes in the atmosphere, both odd zonal time series display strong seasonality. The LAGEOS $J_3$ estimates are very sensitive to as yet unmodeled forces acting on the satellite and these effects must be better understood before determining the dominant geophysical signals contributing to the estimate of this time series.

Introduction

Non-tidal variations in the distribution of atmospheric mass, ocean water mass, continental water storage/snow cover, and ice thickness all cause changes in the gravitational field on time scales of days to decades, but are dominated by seasonality [e.g. Chao et al., 1987; Chao and Au, 1991]. On longer time scales, variations in the solid Earth (e.g. post-glacial rebound) also are sufficiently large that they perturb the orbits of artificial Earth satellites. The cumulative effect of these variations can be studied using satellite tracking data having good spatial and temporal distribution. Satellite laser ranging (SLR) measurements to the LAGEOS satellite collected by a global tracking network between 1980 and 1989 have been used to estimate monthly variations in the second ($J_2$) and third degree ($J_3$) zonal coefficients of Earth's gravitational field. Monthly variations in these zonal coefficients due to atmospheric mass redistribution were also computed using measurements of the variation in surface atmospheric pressure. Results for correlation studies of these two time series follows.

Methods

LAGEOS SLR Data Analysis

Each monthly segment of LAGEOS SLR data was modeled with a continuous orbit estimating the satellite position and velocity at epoch and along-track accelerations parameters for each 15-day segment. The satellite force model consisted of the GEM-T3 gravitational model [Lerch et al., 1992] and an expanded ocean tide model with the 2nd and 3rd degree Sa (annual) and Ssa (semi-annual) ocean tides set to zero. The 18.6 year tide was modeled at equilibrium [Trupin and Wahr, 1990] with an amplitude of 1.22 cm [Cartwright and Edden, 1973]. We used the solid Earth tides according to Wahr [1979]. Solar radiation pressure using a reflectivity coefficient of 1.13, the "Yarkovsky Thermal Drag" [Rubincam, 1988], and corrections for the effects of general relativity [Huang et al., 1990] were employed. The Sa and Ssa degree 2 and 3 ocean tidal terms were set to zero to ensure complete accommodation of all temporally varying 2nd and 3rd degree zonal signals in the recovered $J_2$ and $J_3$ parameters. The observed aggregate zonal mass redistribution could then be compared with the contribution calculated from the atmospheric and other mass transport models. The higher degree terms in the GEM-T3 Sa and Ssa ocean tide models were employed to reduce aliasing arising from their omission.

The IERS Bulletin B Earth rotation series was adopted. Both the geometric and dynamic effects of the rotational deformation of Earth due to polar motion [Wahr, 1985] were modeled. The adopted station coordinates and horizontal velocities for tectonic motions were taken from the solution of Smith et al., [1990] with the NUVEL-1 model [DeMets et al., 1990] used where SLR site velocities were unavailable.

Since tracking data from a single satellite is being used, the LAGEOS $J_2$ and $J_3$ estimates will absorb some signal from the time variations of other higher degree zonal coefficients. This was unavoidable since high correlation precludes the adjustment of additional terms. The effects of temporal variations in $J_2$ and $J_3$ are expected to dominate based on (a) the hemispheric nature of thermal forcing, (b) our modeling of zonal ocean tidal terms of degree 4 through 9 for Sa and degree 4 through 14 for Ssa respectively, and (c) the significant attenuation at LAGEOS' altitude of the geopotential signal.

Atmospheric Pressure Data Analysis

The atmospheric pressure data were processed as described in Chao and Au [1991]. We computed estimates of $J_2$ and $J_3$ over time intervals corresponding precisely to the LAGEOS orbits. The 12-hour pressure fields were derived by the ECMWF by assimilating global meteorological measurements into an atmospheric circulation model. Monthly variations in
$J_2$ and $J_3$ were then computed using all of the 12-hour grids falling within each LAGEOS arc time interval. The analysis was performed both with and without a correction for the ocean’s isostatic response to surface loading, otherwise known as the inverted barometer (IB) effect. The inclusion of the IB effect considerably reduces the contribution of the atmospheric mass over the oceans. The mean values of $J_2$ and $J_3$ were subtracted from their respective time series.

3. Results

**Time Variations in $J_2$**

The secular rate of change of $J_2$, here denoted $\Delta J_2$, determined from the LAGEOS and atmosphere analyses is $-2.6 \times 10^{-11}$/year, and $+1.87 \times 10^{-11}$/year (for both the IB and non-IB cases) respectively; the LAGEOS value is in good agreement with [Yoder et al., 1983; Rubincam, 1984; Cheng et al., 1989]. The LAGEOS rate is given with respect to an equilibrium value of the 18.6-year ocean tide. The atmospheric coefficient time series shows secular trends for many of the zonal harmonics, but these results are not reliable given the changes in the ECMWF computational methods over 1980-89.

Figure 1 compares the LAGEOS and atmosphere $J_2$ time series after removal of the secular rates. The comparison, particularly after 1986, is remarkable considering that LAGEOS senses the combined effects of all global mass redistribution. Most of the variation in $J_2$ occurs at annual/semi-annual periods. Periodic variations were obtained using a least squares fit to the LAGEOS and atmosphere time series. Table 1 presents the resulting unnormalized zonal harmonic coefficients along with estimates of major geophysical contributions to these variations.

The annual variation from LAGEOS compares best in amplitude and phase with the atmosphere/non-IB time series. The actual atmospheric contribution is bounded by the IB and non-IB values; the IB corrected value likely better approximates the atmospheric contribution, for, while there is variation from a complete instantaneous IB effect seen in the ocean’s response to atmospheric loading [Ponte et al., 1991], nevertheless Trupin and Wahr [1990] have shown that the response is essentially that of an IB at longer than 2 month periods. The difference between the LAGEOS and atmosphere/IB annual variations could be accounted for by other annual signals such as that from hydroospheric variations, which are also known to behave with strong seasonality [Chao and O’Connor, 1988; Chao and Au, 1991]. The ocean tides have a small contribution. The hydrological values shown in Table 1 are an incomplete accounting of hydrological mass transport in the absence of the contribution of the ice sheets and groundwater cycles. Nor is mass redistribution within the ocean basins due to wind forcing and changing ocean circulation addressed in these studies given the insufficient monitoring of these effects. This hydrological contribution is likely bounded by the difference between the LAGEOS aggregate values and the part of the signal accounted for by atmospheric and tidal mass redistribution.

Table 1 also shows that the semi-annual variation observed by LAGEOS does not compare as well with the atmosphere results, but the semi-annual variation is mainly forced by variations in the ocean e.g., [Schwiderski, 1980].

There are considerable additional year-to-year and even month-to-month variations that are detected in both the LAGEOS and atmosphere results, especially from 1986-89 when both the SLR technology and the atmospheric model (the ECMWF atmospheric model was substantially changed at the beginning of 1986) are more accurate. If a 10 cm SLR observational sigma is used, the formal errors in the LAGEOS $J_2$ time series range from $2.5 \times 10^{-11}$ during 1980-82 to $1.5 \times 10^{-11}$ during 1983-89. However, these error estimates do not account for aliasing arising from accommodation of the other even zonal effects.

The correlation of the $J_2$ time series was numerically analyzed as follows. The low-frequency signals in the LAGEOS and atmospheric time series are first removed by means of a zero-phase, high-pass filter with a cutoff frequency of 0.5 cycles per year (cpy). The time-domain cross correlation function was then computed for both the non-IB and IB cases. The analysis finds a maximum correlation at zero time shift, with basically the same correlation coefficients of 0.63 for IB and 0.61 for non-IB. The correlation improves to 0.71 and 0.64 respectively when only the 1986-89 data are considered. Since this correlation is being dominated by the annual signal, it is desirable to decompose it spectrally into frequency bands, i.e., in terms of the frequency-domain coherence spectrum. Figure 2 shows the coherence power (magnitude squared) spectra, with respect to the 99% confidence level at 0.67 for 5-point spectral averaging [Chao and O’Connor, 1988]. The high coherence around the (dominant) annual period is evident, while the coherence is rather low at the semi-annual period, confirming the result obtained above. The coherence at 3-4 cpy for the IB case is also notable, reflecting the somewhat higher correlation coefficient than that for the non-IB case. These high-coherence frequency bands are associated with a fairly constant phase close to zero which is consistent with the zero phase shift of the maximum correlation described above.

The low-frequency signals removed above from the LAGEOS and atmospheric time series show considerable interannual variations (amplitudes of $2 \times 10^{-10}$), but the correlation between them before 1986 is rather poor. This poorer correlation results partially from apparent atmospheric data discontinuities caused by operational ECMWF model changes over this period. It could also be indicative of $J_2$ changes caused by other geophysical sources at interannual and longer periods.

**Time Variations in $J_3$**

The secular rate in the change of $J_3$, denoted by $\Delta J_3^*$, determined from the LAGEOS and atmosphere analyses is $-1.86 \times 10^{-11}$/year and $-0.74 \times 10^{-11}$/year (for the non-IB case, but $-0.79 \times 10^{-11}$/year for the IB case) during 1980-89, respectively. This LAGEOS value for $J_3^*$ is larger than previously reported using a Starlette SLR solution [Cheng et al., 1989]. However, if the data from 1989 are excluded from the analysis, the value for $J_3^*$ is $+0.1 \times 10^{-11}$/year, which is similar to this published value.
The time series are in phase from the middle of 1986 to the time series after removing their secular rates. Table 2 shows a large annual variation in $J_3$ is seen in the LAGEOS results. Out of phase and have a larger amplitude. After 1988, what has occurred throughout LAGEOS' lifetime. Currently, this anomaly is unexplained. It is unlikely that it is caused by neglected gravitationally driven ocean tides and is too large to be readily explained by mismodeled non-conservative forces. There is evidence that neglect of "tides" which result from radiative forcing can at least partially explain these effects. Inclusion of these tide-like terms which are known to exist in both the atmosphere and ocean using the radiational potential for the $S_1$ tide as developed by Cartwright and Taylor [1985] is under investigation. Whatever the cause, this unmoded force perturbs the eccentricity of the LAGEOS orbit, which in turn is absorbed into our $J_3$ estimates.

We performed the same high-pass filtering and correlation analysis on the $J_2$ series. The results are much poorer than for $J_2$ as can be expected from Figure 3. There exists a strong annual cross-correlation (around 0.7) with LAGEOS lagging the atmosphere by roughly a month; this is misleading because, being normalized, it only measures relative similarity between the series while disregarding the large difference in amplitude. The corresponding coherence power spectra have a deceptive high coherence at the annual period (but much weaker than the $J_2$ case). There is lack of coherence around the semi-annual period with significant coherence around 4 cpy. There is high coherence around zero frequency in the IB case but is a mere artifact because there is virtually no energy at
zero frequency after the high-pass filtering. The low-frequency signals in $J_3$ are also poorly correlated. The formal errors for the LAGEOS $J_3$ time series range from $4.5 \times 10^{-10}$ during 1980–82 to $2.5 \times 10^{-11}$ during 1983–1989.

Conclusions

We have computed monthly values of variations in the $J_2$ and $J_3$ gravitational coefficients from 1980–1989 using both LAGEOS SLR measurements and surface atmospheric pressure data. The LAGEOS and atmosphere $J_2$ time series agree well, with the primary difference occurring at the semi-annual period where oceanic variations are believed to dominate. At the annual period, the atmospheric results computed without using the IB correction agree better with the LAGEOS results, although the difference at the annual period between the IB and the LAGEOS results could be explained by other phenomena such as hydrologic mass redistribution.

The atmosphere and LAGEOS results for $J_3$ have poorer agreement. This is evident in the unexplained annual power seen in the LAGEOS $J_3$ time series, and especially in 1989 where the LAGEOS results show strong amplification of this effect. This behavior must be explained and accounted for before these results can be interpreted for mass redistribution effects. The analysis of post-1989 SLR data has shown repeat of the anomaly again in 1991–92. The cause of this anomaly is under investigation with neglected "radiational tides" in our analysis being a candidate explanation.

These initial results have shown that LAGEOS SLR data can be used to detect small variations in the gravitational field. The results of this study also have important ramifications for studies of the static gravitational field, as variations in the atmosphere will probably require that lengthy (>1 year) sets of observations be collected. This requirement could be relaxed if the gravitational variations due to the atmosphere can be sufficiently modeled using the surface pressure measurements.

Acknowledgments. The contributions of the GEODYN Software Development Team, headed by B. H. Putney, and the GSFC SLR Analysis Group, headed by D. E. Smith, are gratefully acknowledged. We also acknowledge useful discussions we have had with Richard Eanes of the Center for Space Research at the University of Texas at Austin in addition to his thorough review of this paper.

References


